FORMATION EVALUATION THROUGH COMBINED USE OF CORE ANALYSIS AND ELECTRICAL RESISTIVITY LOGS

C. K. OSBORN
Core Laboratories, Inc.

INTRODUCTION

Information essential to interpretation of hydrocarbon and/or water productivity is not available from a single measurement technique, whether it be core analysis, complete suites of electrical logs or bottomhole pressure build-up or fall-off tests.[1] The best features of each technique can be combined to obtain mutually consistent interpretations which result in improved evaluation of potentially productive intervals in a well.

Methods are described which combine core analysis data with electrical resistivity logs. This combination yields information required to select zones for completion, zonal producing characteristics and their possible down-dip productive limits. To accomplish this, core analysis and appropriate reservoir fluid data are converted to values of resistivity. These values are plotted on transparent overlays which are compatible with resistivity scales reported on the downhole resistivity log.

THEORETICAL CONSIDERATIONS

Basic Resistivity Equations

The resistivity of a formation is governed by its porosity, pore geometry and the properties and saturations of the fluids within the pores. Relationships to describe the effects of these variables on resistivity have been reported by several workers, but those developed by Archie[2] are presented as they are used in this study:

$$R_o = R_w\ (1/\phi^m) = R_w\ (F) \qquad (1)$$

$$R_t = R_o\ (1/S_w^{\ n}) = R_o\ (RI) \qquad (2)$$

Many well completions have been, and are being, made employing gross assumptions relative to values for most of the variables in these equations. There is often a tendency to discredit the limited measured data available when interpretations prove erroneous, even though insufficient measured data is the source of error.

Reliable values of porosity, pore size and distribution, permeability, variation of formation factor (R_o/R_w) with porosity, and variation of resistivity index (R_t/R_o) with water saturation can be measured through core analysis. Modern downhole resistivity logs such as the dual induction-laterolog and the dual laterolog normally yield reliable values of formation true resistivity. The remaining variable in Eqs. (1) and (2) is formation water resistivity. The significance of this variable cannot be overemphasized.

Sources available for R_w determination range from direct measurement on water samples to analogy. Normally, a value or range of R_w can be established for a specific location. In the absence of specific knowledge the "range" approach is recommended. The procedures presented in this paper lend themselves to either approach.

R_o as a Basis for Evaluation

The wide variance in formation resistivity found in many low to medium porosity reservoirs is primarily due to rapid increase in formation factor as porosity decreases. Increasing interstitial water saturation that often accompanies a decreasing porosity tends to counteract this resistivity increase. In hydrocarbon productive zones these opposing forces on formation resistivity may, at times, cancel each other leaving essentially no change in log true resistivity through large variations in water saturation exist.[1]

R_o can be calculated by using Eq. (1) for each core sample obtained from a zone of interest using measured values of porosity, cementation factor "m", and an appropriate value for R_w. The magnitude of difference between each R_o value and its comparable downhole R_t value at a common depth reflects both the quantity and distribution of the in situ water saturation. Equation (2) can be solved for water saturation if the slope "n" of the resistivity index versus water saturation curve is properly determined through statistical analysis of measured data.

Conversion of Water-Cut Data to Equivalent Resistivity Values

Many interpretations end with the determination of water saturation. "Rules of thumb" are then employed to predict quantity of water production. Knowledge of saturation conditions in a two-phase reservoir system permits the computation of fractional flow of water in the reservoir if the fluid mobilities corresponding to these conditions of saturation are known. This fractional flow can then be converted to surface water-cut using an appropriate formation volume factor. This computation employs two-phase relative permeability as a function of water saturation for the complete range of rock properties encountered and reservoir fluid viscosities.[3]

If it is desired to determine the interstitial water saturation that would yield a known or arbitrary water-cut, it is a simple matter to reverse the above procedure. This approach permits the arbitrary selection of a range of water-cuts and determination of corresponding water saturations. The water saturations thus determined can then be converted to values of resistivity for direct comparison to a downhole resistivity log.

Conversion of a surface water-cut to water-oil relative permeability ratio is described by Eqs. (3) and (4):

$$f_w = \frac{WC}{\left[B_o\,(1-WC) + WC\right]} \qquad (3)$$

$$k_w/k_o = \frac{1.0}{\dfrac{(1-f_w)}{f_w}\,\dfrac{\mu_o}{\mu_w}} \qquad (4)$$

Having computed the water-oil relative permeability ratio corresponding to a given water-cut and having the appropriate relative permeability versus water saturation relationship, water saturation corresponding to the given water-cut can be determined. Using Eq. (2), R_t for the determined water saturation can be calculated.

Examples presented in this study are confined to oil-water systems. The procedures for a gas-water system require only an alteration of the mathematics.[4]

Conversion of Height Above Zero Capillary Pressure to Equivalent Resistivity Values

There is often concern as to the height a given zone of completion is above a water-oil level. Height above zero capillary pressure versus water saturation relationships can be developed for a complete range of rock properties encountered. The best available measured data should be used in assigning values of fluid density, interfacial tensions, and contact angles in converting capillary pressure to height.[5,6] This relationship can then be entered with the core analysis-resistivity log interpreted water saturation, and height can be determined. This is possible only if the water saturation is greater than irreducible. At irreducible water saturation only the minimum height can be determined. Many low to medium porosity reservoirs exhibit excessively long transition zones,[7] thus making height determinations more practical.

To make this interpretation directly applicable to a resistivity log, it is necessary to select a range of heights covering the entire transition zone. Saturations are then determined at each height from the height versus water saturation relationships. Using Eq. (2) these saturations may be converted to resistivity.

LIMITATIONS OF PROCEDURES

Measured reservoir rock and fluid properties for each specific reservoir should be used in these calculations. In the absence of measured relative permeability, capillary pressure and reservoir fluid data for a specific reservoir, statistical correlations for the regional formation in which the reservoir occurs will sometimes yield usable results.[7]

Care should be taken so as not to underestimate reservoir pressure used to select fluid characteristics, particularly in in-fill programs in low to medium porosity reservoirs. In-fill wells often exhibit reservoir pressures approaching initial values rather than the reduced pressures measured in old producing wells over a short term build-up.

The procedures and techniques employed are applicable only to water-wet or essentially water-wet reservoirs where only two phases saturate the rock. Large solution cavities and open fracture systems exposed to the well bore diminish the effectiveness of the procedures. Only those resistivity logs which are plotted on a logarithmic scale are applicable.

Experience to date has shown that application of these techniques to zones having permeability of less than 0.1 millidarcies is not warranted. Therefore, a plot of permeability with depth on the five inch to 100 feet scale is recommended as a guide to interpretation as shown on Fig. 1.

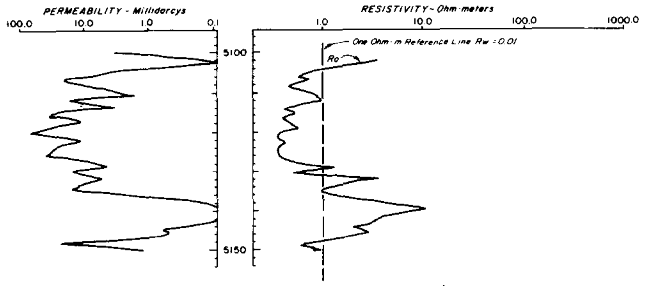

FIG. 1—THE R_o OVERLAY

PREPARATION AND APPLICATION OF THE R_o OVERLAY

An R_o value is calculated for each sample of core analyzed using Eq. (1). An arbitrary value of 0.01 ohm-meters is used for R_w. Appropriate values of cementation factor "m" are employed for each porosity. These R_o values are plotted on a logarithmic grid corresponding to that used on the electric log at the appropriate core depth. The points are then connected. A transparent overlay is prepared from this plot showing only a 1.0 ohm-meter reference line for R_w equal 0.01 ohm-meters, and the R_o curve as shown on Fig. 1. Permeability is plotted on the left-hand track of the overlay for ready reference.

The overlay approach has two advantages over plotting the R_o curve directly on the electrical resistivity log. Firstly, experience has shown that depth adjustment is not constant when orienting core analysis data with downhole logs, particularly when interpreting long intervals.[1] Secondly, the use of an arbitrary R_w in overlay preparation permits employment of a range of actual R_w values in the interpretation.

The application of the overlay to the downhole log is done through simple multiplication on the logarithmic scale using the appropriate R_w.[1] For example, if the actual R_w were 0.1 ohm-meters rather than the arbitrary value of 0.01 used in constructing the plot, it would be necessary to multiply all computed values of R_o by a factor of ten to yield a true reservoir value. This is accomplished by orienting the overlay on the electric log with the 1.0 ohm-meter reference line coincident with the 1.0 ohm-meter line on the log, and then shifting the overlay to the 10.0 ohm-meter line on the log. Figure 3 depicts this example after shifting the overlay. The R_o curve thus oriented on the resistivity log forms the basis for interpretation of a zone of interest.

BASIC SCALER FORMAT

Interpretations of water production characteristics, interstitial water saturations and heights above zero capillary pressure can be accomplished through the use of transparent scalers which can be oriented to the 1.0 ohm-meter reference line on the R_o overlay. Each of the three required scalers are constructed on the same basic format. One ohm reference and R_o index lines are common for each set of scalers described for a given set of rock and fluid data as shown on Figs. 2, 4 and 6.

A log-log resistivity grid is used in scaler construction with the abscissa being identical to the downhole log resistivity scale and the *ordinate* being an arbitrary logarithmic scale larger than the abscissa to minimize scaler width. A (0.2, 0.2) ohm-meter coordinate is located in the upper left-hand corner of the grid with resistivity increasing to the right on the abscissa and toward the bottom of the scaler on the *ordinate.*

Values of porosity are selected arbitrarily in increments covering the complete range of porosity encountered in the well or wells to be evaluated. The number of porosity values selected could vary with conditions; however, in low to medium porosity formations 10 to 15 values are suggested. Using the proper cementation factor "m" and an R_w equal to that used in construction of the R_o overlay, compute R_o for each porosity selected. Plot these R_o values on the scaler grid and connect the points with a straight line, thereby creating the R_o index line. Also, if the scalers are being prepared by hand, it is desirable to draw lines perpendicular to the *ordinate* through each R_o value to facilitate plotting of the various scaler curves. The one ohm reference lines as depicted on Figs. 2, 4 and 6 are coincident with the one ohm line on the abscissa of the scaler grid.

PREPARATION AND APPLICATION OF THE SCALERS

The Water-Cut Scaler

The construction of the water-cut scaler requires arbitrary selection of water-cut values covering a range from low to high. Figure 2 shows the values selected for a West Texas carbonate. The following is then completed for each value of porosity used in construction of the R_o index line. At each value of water-cut selected, the water-oil relative permeability ratio is calculated using Eqs. (3) and (4). The relationship of water-oil relative permeability ratio versus water saturation is then entered to yield a water saturation corresponding to the selected water-cut. Values of R_t for the given water-cut are computed for the water saturations using Eq. (2). The R_o value computed for each porosity in the range and the appropriate value of saturation exponent "n" must be employed.

These R_t values are plotted on the basic scaler grid directly opposite the corresponding *ordinate* R_o value. The points are connected with a smooth curve. Each water-cut value in the selected range is handled in the same manner.

A transparent overlay showing only the reference lines and water-cut curves is prepared from a tracing. An example scaler for a West Texas carbonate is presented on Fig. 2.

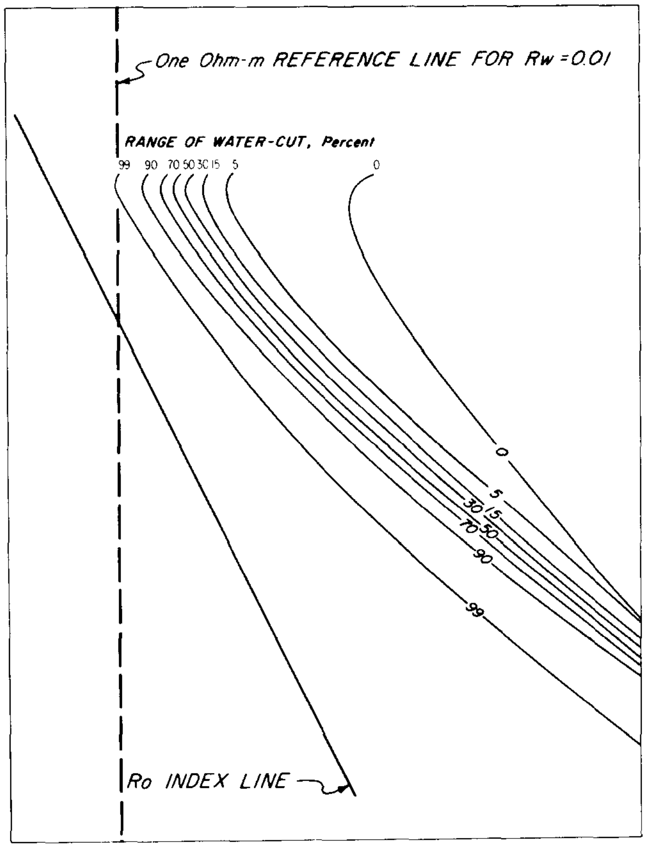

FIG. 2—SCALER FOR WATER-CUT DETERMINATION

To orient the scaler, first make sure the R_o overlay has been properly oriented to the resistivity log with respect to both depth and R_w. Then lay the scaler 1.0 ohm-meter reference line directly on the oriented R_o overlay one ohm-meter reference line. Interpretations of zonal water-cut behavior may be made by sliding the scaler vertically until the R_o index line intersects the R_o curve at a point of interest. Values of water-cut are read where the corresponding point on the R_t log intersects the water-cut lines. The example presented on Fig. 3 shows the intersection of the R_o index with the R_o curve at Point A. Reading directly across to Point A′ a water-cut value of approximately, 3.0% is read.

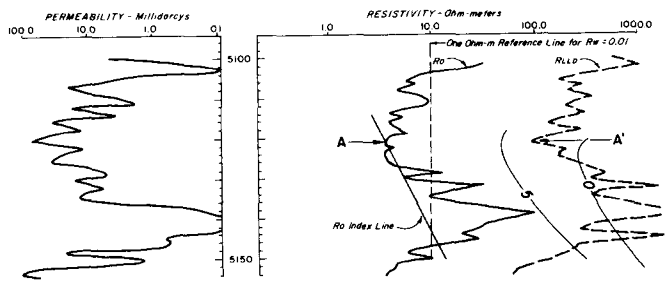

FIG. 3—APPLICATION OF WATER-CUT SCALER

The water-cut scaler is useful in selecting zones of completion and length of perforated intervals. This is particularly true when evaluating thick formations with wide variation in porosity and permeability, such as that exhibited by West Texas carbonates.

The Water Saturation Scaler

Various service companies have provided scalers for interpretation of interstitial water saturation for several years. The principle of scaler construction presented here is the same as that previously used. The only difference is the scaler format and application. There is an advantage in employing this scaler in the case of cementation factor "m" and/or saturation exponent "n" varying with a variation in measured rock property.

After constructing the one ohm reference and R_o index lines, select a range of water saturations from a low to high limit with arbitrary intermediate incremental values such as those shown on Fig. 4. For a given incremental value of water saturation compute the R_t that would be exhibited by each value of porosity employed in constructing the R_o index line using Eq. (2). Plot these R_t values opposite the *ordinate* values of R_o on the basic scaler grid and connect the points with a smooth curve. Each incremental value of water saturation is handled in a like manner. Having constructed the curves prepare a transparency showing only the water saturation curves and the reference lines.

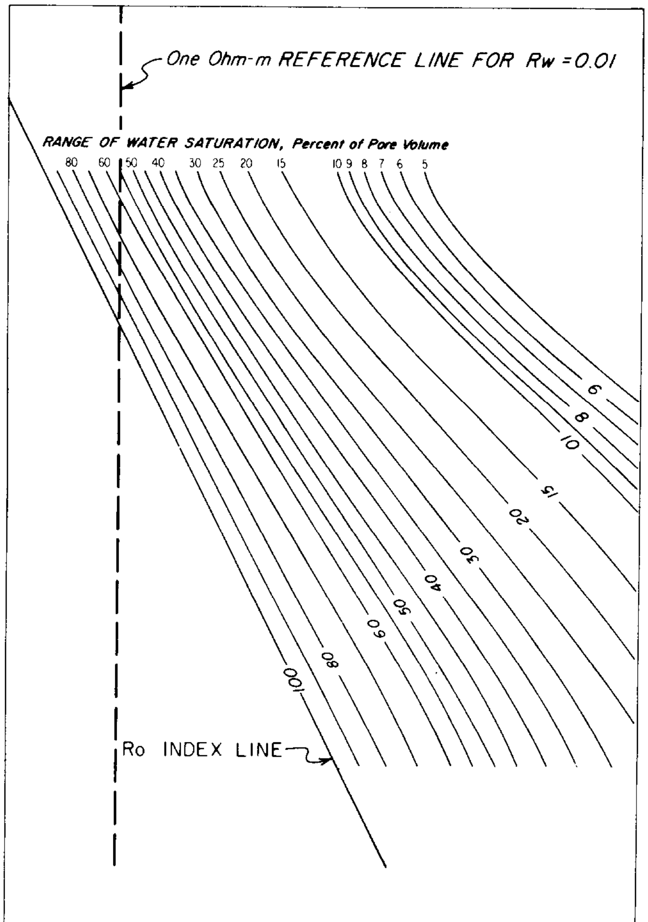

FIG. 4—SCALER FOR WATER-SATURATION DETERMINATION

The orientation and use of the water saturation scaler on the combined R_o curve and resistivity log is accomplished in the same manner as that described for the water-cut scaler. The example shown on Fig. 5 describes the intersection of the R_o index line with the R_o curve at Point A. Point A', directly opposite Point A on the resistivity log, indicates a water saturation of approximately 15%.

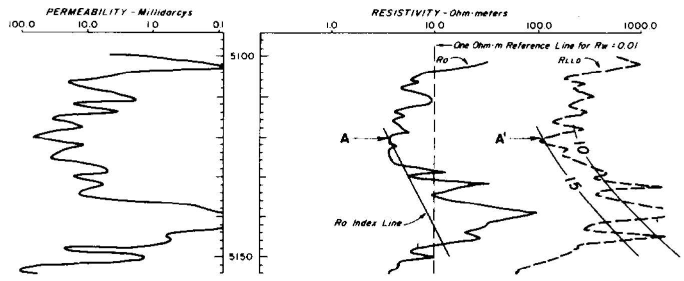

FIG. 5—APPLICATION OF WATER SATURATION SCALER

The scaler is particularly useful in digitizing water saturation distribution in selected zones of completion for quick evaluation of hydrocarbons in place. There have been occasions where in-fill drilling programs have been conducted in waterflood projects. When precise R_w data are obtained for a zone of interest, it is possible to make a statistical evaluation of residual oil saturation. This information, coupled with production test data from the zone, yields information relative to recovery versus water-cut behavior. If the zone produced at a water-cut equivalent to limiting economic conditions, an estimate of waterflood residual oil saturation at abandonment of waterflood operations could be made. The water-cut scaler could be used in lieu of actual production test data for a statistical evaluation.

The Height Scaler

A scaler indicating height of a zone above zero capillary pressure is prepared by selecting arbitrary increments of height from a low to a high value over a range considered adequate. The range should be selected within the limits of the transition zones described by the capillary pressure curves used. Figure 6 shows the range of values selected for a West Texas carbonate exhibiting a long transition zone.

For each arbitrary height, select values of water saturation from a height versus water saturation relationship for each value of porosity used in

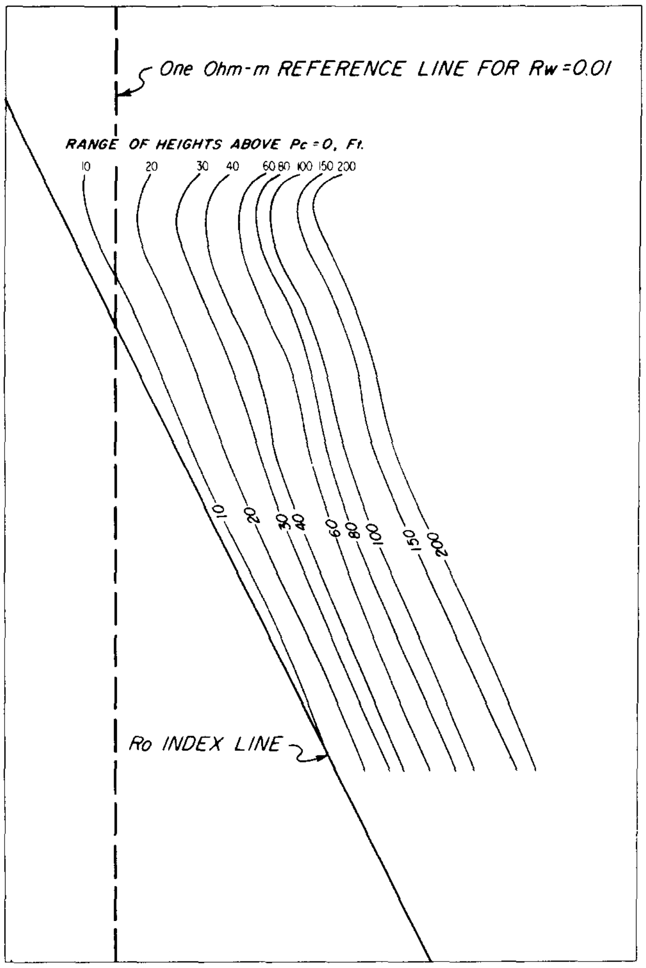

FIG. 6—SCALER FOR HEIGHT DETERMINATION

constructing the R_o index line. If the height versus water saturation relationship has been established using permeability as a controlling parameter, it will be necessary to have a statistical correlation between permeability and porosity to accomplish conversion.

The water saturations for a given height thus established are converted to resistivity using Eq. (2). These resistivities are then plotted opposite their appropriate *ordinate* R_o value on the basic scaler grid and a smooth curve is drawn through the points. Curves for each selected height are drawn employing the same procedure. The transparency is made in the same manner as that described for the other scalers. An example height scaler is shown on Fig. 6.

The method of applying the height scaler is the same as that described for the water-cut scaler. The example shown on Fig. 7 indicates the points A-A′ to be approximately 150 ft above zero capillary pressure.

Best results from this scaler are obtained in evaluating transition zones; therefore, be sure that the zonal characteristics being evaluated are in this region or an excessive height may result. In reservoirs with wide variation in rock characteristics it is suggested that heights be digitized within a zone of interest and averaged to obtain the best statistical result.

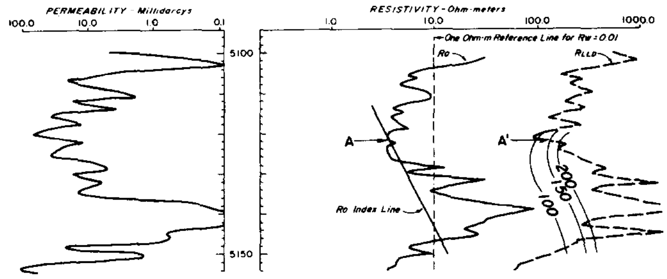

FIG. 7—APPLICATION OF HEIGHT SCALER

In evaluating an exploratory well, interpretations from application of this scaler should be of value in locating water-oil levels and describing lower limits of completion. Also, these data should be of material benefit in locating additional wells on a structural interpretation.

In-fill well evaluation could benefit in the same manner as that described for the exploratory well, with one additional benefit. Interpretation from capillary pressure data requires that a reservoir be in capillary equilibrium. Therefore, if water influx has occurred in mature fields, this should be detectable in in-fill wells evaluated with this scaler by observing inconsistencies in height within a reservoir. This interpretation is complicated in multizone fields due to the possibility that a multireservoir situation exists. However, well studies employing this technique should confirm one or the other of both eventualities.

CONCLUSIONS

A combination of measured formation rock and fluid properties and deep investigating resistivity logs will yield statistically accurate formation evaluation. This provides zonal water production characteristics, interstitial water saturation, and height above zero capillary pressure.

A unified system of interpretation can be developed by converting measured reservoir rock and fluid data to equivalent resistivity and constructing a set of transparent overlays which can be directly applied to the downhole log. This system permits a maximum amount of data to be used in well evaluation with minimum time consumption.

NOMENCLATURE

B_o - Oil formation volume factor, vol/vol
F - Formation Factor (R_o/R_w or $1/\phi^m$)
f_w - Fractional flow of water, frac.
k_o - Effective permeability to oil, md
k_w - Effective permeability to water, md
m - Cementation factor (slope of formation factor vs. porosity curve)
n - Saturation exponent (slope of resistivity index vs. water saturation curve)
RI - Resistivity Index (R_t/R_o or $1/S_w{}^n$)
R_o - Resistivity of formation saturated 100% with formation water, ohm-meters
R_t - True resistivity of formation, ohm-meters
R_w - Resistivity of formation water, ohm-meters
S_w - Interstitial water saturation, frac.
WC- Water-cut, frac. (Produced water vol. divided by produced oil vol. plus produced water vol.)
ϕ - Porosity, frac.
μ_o - Viscosity of reservoir oil, cp
μ_w - Viscosity of reservoir water, cp

REFERENCES

1. Granberry, R.J., Tucker, L.E.: CoRes Log - A Core Analysis and Resistivity Evaluation Log, paper presented at SPWLA 14th Logging Symposium, May 6-9, 1973.
2. Archie, G.E.: The Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics: *Petr. Tech.*, vol. 5, no. 1, 1942.
3. Amyx, J.W.; Bass, D.M., Jr.; and Whiting, R.L.: "Petroleum Reservoir Engineering - Physical Properties," McGraw-Hill Book Co., Inc., New York, 1960, pp. 133-209.
4. Pirson, S.J.: "Handbook of Well Log Analysis," Prentice-Hall, Inc., Englewood Cliffs, N.J., 1963, p. 43.
5. Core Laboratories, Inc., *Special Core Analysis and Industrial Water Technology Manual,* Core Laboratories, Inc., Dallas, Texas, Apr. 1970, pp. 26-29.
6. Muskat, M.: "Physical Principles of Oil Production," McGraw-Hill Book Co., Inc., New York, 1949, pp. 271-296.
7. Osborn, C.K., and Hogan, C.A.: Corecom - A Practical Application of Core Analysis, Proceedings of the 19th Ann. Mtg., Southwestern Petroleum Short Course, Apr. 1972, pp. 75-80.

ACKNOWLEDGMENTS

The author wishes to thank R.J. Granberry and C.A. Hogan of Core Laboratories, Inc., for their valuable assistance. Thanks are also extended to Cities Service Oil Co. for the well logs and basic core analysis data used in the examples.